

Contents

<i>Preface</i>	xi
<i>Introduction</i>	xiii
1. What Makes the World Tick?	1
1.1 Motion	1
1.2 Gravitation	2
1.3 The force field	4
1.4 Equivalence principle	4
1.5 Energy	6
1.6 Momentum	7
1.7 Least action	7
1.8 Newton canonized	9
1.9 The mechanical universe	10
2. Electromagnetism	13
2.1 Electric field	13
2.2 Lines of force	14
2.3 Multipoles	14
2.4 Scalar potential	15
2.5 Electric current	16
2.6 Magnetic field	16
2.7 Vector potential	18
2.8 Electromagnetic induction	18
2.9 Maxwell's equations	19

2.10	Radiation	22
3.	The Vacuum is the Medium	25
3.1	The ether	25
3.2	Reference frames	26
3.3	The light cone	28
3.4	Lorentz transformation	28
3.5	Relativity of space and time	30
3.6	Four vectors	31
3.7	$E = mc^2$	32
3.8	Faster than light?	33
3.9	Maxwell's true form	33
3.10	The gauge field	34
3.11	Who wrote these signs	35
3.12	Lorentz and Einstein	36
4.	Let There be Light	39
4.1	Local gauge invariance	39
4.2	A creation	40
4.3	The gauge principle	42
4.4	Hermann Weyl	43
4.5	And there was light	45
5.	Heroic Age: The Struggle for Quantum Theory	47
5.1	Alien signals	47
5.2	Bohr's atom	49
5.3	Purely imaginary	52
5.4	Quantum mechanics	54
5.5	The wave function	55
5.6	Quantum theory and relativity	56
5.7	Silly question	57
6.	Quantum Reality	59
6.1	The uncertainty relation	59
6.2	Wave nature of matter	60

6.3	Entanglement	61
6.4	All virtual realities	64
6.5	The quantum century	66
6.6	<i>The Waste Lecture</i>	67
7.	What is Charge?	69
7.1	The quantum gauge	69
7.2	Covariant derivative	70
7.3	Aharonov–Bohm experiment	71
7.4	U(1)	73
7.5	Quantum gauge principle	74
7.6	Global vs. local gauge invariance	75
8.	The Zen of Rotation	77
8.1	Rotations do not commute	77
8.2	Hamilton’s flash of insight	78
8.3	Generators of rotation	80
8.4	Groups	80
8.5	SU(2): fundamental representation	81
8.6	The adjoint representation	83
9.	Yang–Mills Field: Non-Commuting Charges	85
9.1	Gauging SU(2)	85
9.2	Picturing local gauge invariance	88
9.3	Maxwell generalized	88
9.4	Gauge photons	90
9.5	Magnetic charge	91
9.6	Monopole: the gauge hedgehog	91
9.7	Into the deep freeze	93
10.	Photons Real and Virtual	95
10.1	Real photons	95
10.2	Quantum jumps	97
10.3	Virtual photons	99

11. Creation and Annihilation	101
11.1 The quantum field	101
11.2 Particle and antiparticle	103
11.3 The Dirac equation	104
11.4 The Dirac sea	105
11.5 Reversing time	106
11.6 Feynman diagram	108
11.7 The fine-structure constant	111
12. The Dynamical Vacuum	113
12.1 QED	113
12.2 Interaction vertex	113
12.3 Self-energy	114
12.4 Vacuum polarization	115
12.5 The dressed electron	116
12.6 The ultraviolet catastrophe	117
12.7 Reality of vacuum fluctuations	119
12.8 When physicists were heroes	122
12.9 The enduring QED	123
13. Elementary Particles	127
13.1 Beginnings	127
13.2 Bosons and fermions	132
13.3 Spin and statistics	134
13.4 Interactions	135
14. The Fall of Parity	139
14.1 Dawn of the post-modern era	139
14.2 Neutrino: a left-handed screw	142
14.3 CP	143
14.4 Is nothing sacred?	144
15. The Particle Explosion	147
15.1 The accelerator boom	147
15.2 Darkness at noon	150

15.3	The ontological bootstrap	152
15.4	The ultimate temperature	155
15.5	Echos of an era	156
16.	Quarks	157
16.1	Strangeness	157
16.2	Octet and decaplet	158
16.3	The eightfold way	160
16.4	“Three quarks for Muster Mark!”	162
16.5	Charm and beyond	163
16.6	Partons	163
16.7	Charmonium	164
16.8	Color	166
17.	All Interactions are Local	169
17.1	Yang–Mills awakens	169
17.2	Unifying electromagnetic and weak interactions	170
17.3	Generating mass	172
17.4	Making the photon	173
17.5	Historical note	174
17.6	The lepton-quark family	175
17.7	QCD	176
17.8	Two more families: who ordered them?	177
17.9	The standard model	179
18.	Broken Symmetry	181
18.1	What is mass?	181
18.2	How a magnet gets magnetized	182
18.3	The order parameter	184
18.4	The Goldstone mode	186
18.5	Superconductivity: the photon gets mass	188
18.6	Historical note	189
19.	Quark Confinement	193
19.1	Monopole confinement	193
19.2	Electric flux tube	194

19.3	The QCD string	197
19.4	Asymptotic freedom	198
20.	Hanging Threads of Silk	201
20.1	Mass	201
20.2	Chirality	203
20.3	The pion as Goldstone boson	204
20.4	PCAC	205
20.5	The triangle anomaly	207
20.6	Lepton-quark family structure	209
20.7	Waiting for closure	211
21.	The World in a Grain of Sand	215
21.1	A matter of scale	215
21.2	Renormalization	217
21.3	The running coupling	219
21.4	Fixed point: theoretical model	222
21.5	UV fixed point: QCD	222
21.6	IR fixed point: QED	223
21.7	Crossover: scientific revolution	225
22.	In the Space of All Possible Theories	227
22.1	The physics is in the cutoff	227
22.2	The RG trajectory	228
22.3	The space of Lagrangians	231
22.4	Of time and temperature	232
22.5	<i>Tian Wen</i>	234
22.6	<i>Tian Wen</i> updated	236
	Epilogue: Beauty is Truth	237
	Appendix. Nobel Prize in Physics	239
	Annual listing	239
	Alphabetical listing	257
	Name Index	261
	Subject Index	265